

# Development of the Second Generation Wide Field Planetary Camera for Hubble Space Telescope

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## OVERVIEW

The Wide Field and Planetary Camera (WFPC) is the principal instrument of the Hubble Space Telescope (HST), occupying the central portion of the telescope's focal plane. The Wide Field Camera meets the originally conceived requirement for an imaging device that covers a square field of view 2.67 arc minutes on a side with a pixel size of 0.1 arc second. The so-called Planetary Camera of WFPC offers a longer effective focal length over a smaller field (yielding 0.043 arc second per pixel) to better sample the point spread function of the telescope for critical definition imaging. The first generation WFPC (WFPC-1) was initiated in late 1977 and launched with the HST in April, 1990. A second generation backup instrument (WFPC-2) currently scheduled for launch in late 1993 will carry corrective optics to restore the flawed vision of the HST. The present paper traces the history of these developments.

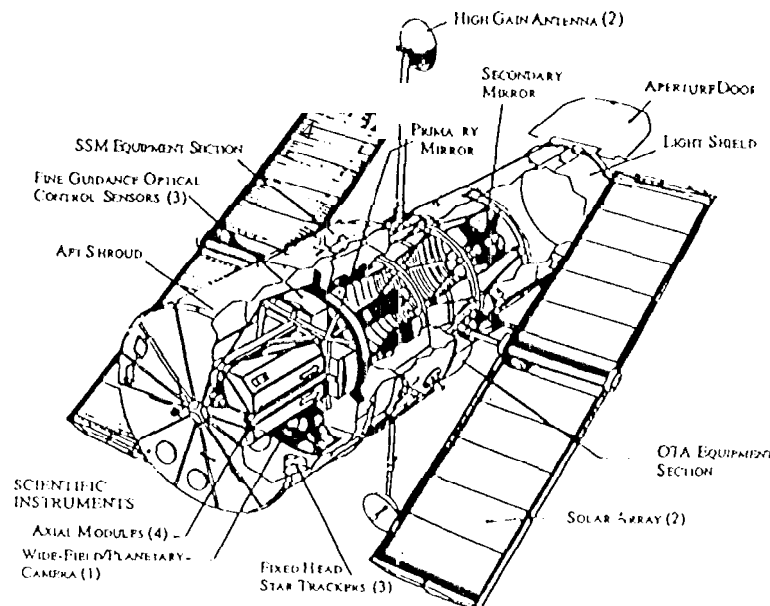
## EARLY HISTORY

The concept of a large astronomical telescope orbiting above the Earth's atmosphere [1] was first proposed by Prof. Lyman Spitzer, Jr. of Yale University (later professor at Princeton University) in the late 1940's. A telescope operating above the atmosphere has many inherent advantages over ground based observatories: resolution is not degraded by atmospheric "seeing" and so can approach a limit imposed only by diffraction; the accessible spectral region can be extended far into the vacuum ultraviolet below 330nm, which is inaccessible to ground based observatories because the atmosphere is opaque at these wavelengths. An orbiting observatory can also operate around the clock.

After the formation of NASA the concept was studied extensively in the '60's and early '70's. First conceived as the "Large Space Telescope" (LST) of up to 5 meters' aperture, its name was later changed to Space Telescope (ST) when the Space Shuttle became the launch vehicle of choice in 1971-2, and the ST's aperture had to be constrained to fit within the cargo bay of the Shuttle. When the ST Project was approved for flight under the direction of the Marshall Space Flight Center in late 1976 (the start of fiscal 1977) the baseline design called for a 2.4m F/24 telescope with five scientific instruments or SIs as they are called. In addition, there were of course all the usually required spacecraft systems plus a very high performance pointing control system using a set of Fine Guidance Sensors (collectively called the FGS). The FGS is capable of stabilizing the observatory to within 0.007 arc seconds for extended periods of time. Figure 1 shows a cutaway drawing of the completed observatory.

#### HST CUTAWAY DRAWING

FIGURE 1.



#### WFFC Science Capabilities

An additional and unique constraint (for a scientific observatory) was the requirement imposed on the ST that it be designed to be serviced in space. This concept uses the Space Shuttle to carry astronauts to engage in Extra Vehicular Activities for servicing purposes. The first demonstration of this capability

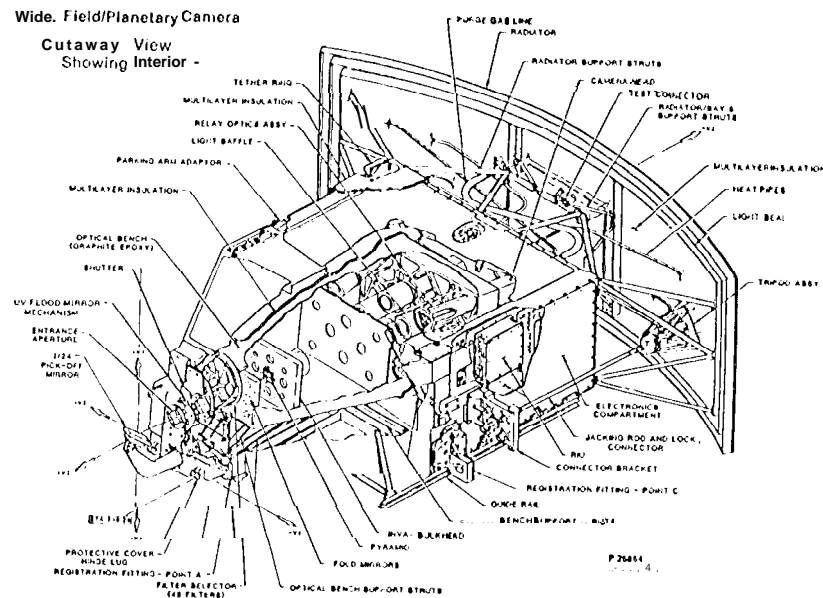
will be the servicing mission scheduled for 3ate1993, in which corrective optics for the flawed HST primary will be installed, along with other repairs and rep) accements.

## THE FIRST GENERATION WFPC

The instrument that became WFPC-1 was selected on a competitive basis as a PI (Principal Investigator) instrument through an Announcement of Opportunity issued by NASA in 397 [ 5 ] . Prof. James A. Westphal of Cal tech and his team were selected in 19"/7 to develop it as the prime imaging instrument. Prof. Westphal had arranged for the camera to be built by Jet. Propulsi on laboratory (JPI), which is managed by Cal tech for NASA. At the time of selection the camera was to be delivered in 1980 for a 1982 launch. The concept of the camera evolved rapidly in the early post-proposal phases of its design, ultimately acquiring the dual focal ratios that led to the name WFPC. Figure 2 is a cutaway drawing showing the principal features of WFPC-1 .

## CUTAWAY DRAWING OF WF/PC-1

FIGURE 2.



Replacement instruments were to be available to support Servicing Missions on a five year incremental time interval. Delays and changes in the Shuttle development program caused consequential delays in the development of both the ST and the SIs associated with it. This resulted in delays to both the launch and the initiation of the development of the "second generation" scientific instruments. In 1984 with the ISSI scheduled for launch in 1986, a decision was made to obtain a duplicate -- or "clone" -- of the first WF/PC to ensure that the HST imaging capability was backstopped. This second camera was to be delivered in 1988 [2]. With the Challenger accident of January 1986, the planned launch of the HST was delayed to 1989. Clearly the second camera would not be required as early as 1988; hence its development was stretched out to preserve resources. A fortuitous scientific result of this circumstance was the opportunity to reassess the requirements for achieving good UV performance of the instrument. In particular, the performance shortward of 200nm was of great interest and some judicious improvements were identified to ensure that the FUV performance of the camera would not be compromised. Key issues were (1) the use of materials that had ultra-low outgassing properties, (2) use of materials that would not tend to condense on surfaces at -100°C, (3) development of improved FUV CCD performance, and (4) selection of an upgraded filter set.

The HST was launched on April 24, 1990 from the Kennedy Space Center. At that time, the second camera was scheduled for delivery in the 1995 time frame.

### SPHERICAL ABERRATION

The first images returned from the observatory in May of 1990 showed abnormal characteristics and various difficulties were encountered in "fine tuning" the telescope's performance. From extensive examination of the images the conclusion was reached by the science team and workers at JPL, and the Space Telescope Institute, that the HST optics were flawed by a large measure of spherical aberration.

It was recognized almost from the outset that if the primary mirror of the HST happened to be the cause of the problem (as the result of having an incorrect aspheric shape), the fix would be relatively straightforward, at least for WFPC. In WFPC there are eight two-mirror relays that serve to re-image the prime focus of the telescope onto the detectors at  $F/12.9$  (for the WFC mode) and  $F/30$  (for the PC). For technical reasons these optical systems were designed to form real images of the HST primary mirror at certain locations within each relay camera. In the case of the WFC the HST primary mirror is re-imaged at precisely the position of a small convex mirror serving as the relay secondary mirror of the relay. In the PC, the HST primary is reimaged relatively close to the

relay secondary. Hence it came about that a defect of the HST primary could be compensated by introducing an equal but opposite "defect" on small elements located at or near an image of the HST primary. This is illustrated in figure 3.

It was not initially known whether in fact the defect could be ascribed to the primary mirror of the telescope, or whether it was caused wholly or partly by errors of the secondary mirror of the telescope. If significant errors of the secondary of HST were involved, the simple fix in WFPC could not correct the problem except for a tiny fraction of the intended full field of view of the instrument.

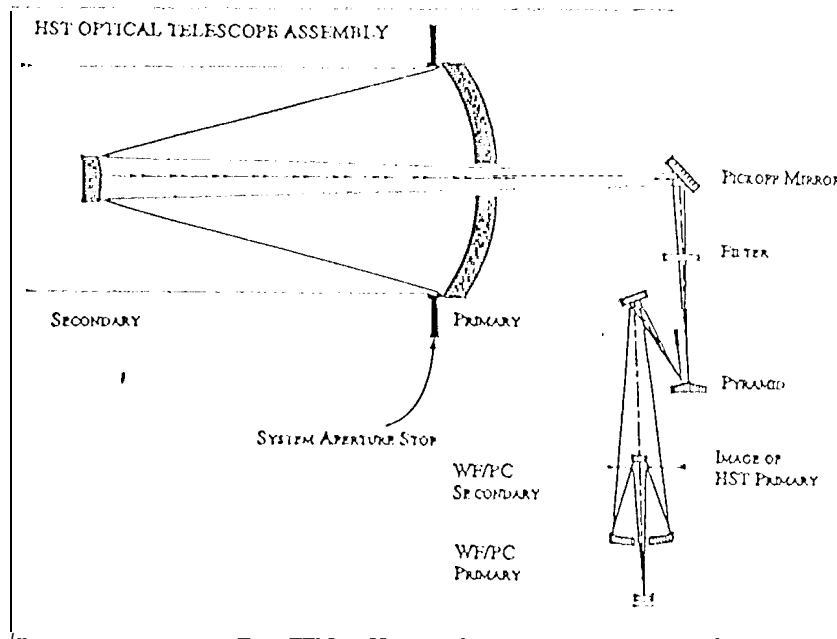
The exact nature of the defect and the fact that it is restricted to the HST primary mirror were eventually well established, but extensive studies were necessary to establish these parameters in the year following the discovery of the problem. A Board of Inquiry had been set up under the chairmanship of JPL Director Dr. Lew Allen[3], to determine how an error had occurred and escaped detection during the manufacturing process.

A second, more detailed technical investigation of the aberration was conducted by a team known as the Hubble Independent Optical Review Panel (HIORP), chaired by Prof. Duncan Moore of the University of Rochester's Institute of Optics and sponsored by the Goddard Space Flight Center (GSFC) under the leadership of Dr. H. John Wood[4,5]. In particular, it became the primary responsibility of the HIORP to fully characterize the optical system of HST through studies of the optical test tooling used in making the optics as well as through analysis of the on-orbit images -- activities that came to be known as "image inversion analysis" and "prescription retrieval". The investigations of the HIORP eventually converged to show that the only significant defect was that the HST primary mirror's hyperbolic shape had an incorrect eccentricity: its conic constant was somewhere between -1.0135 and -3.0340, instead of the intended value of -1.0023. This meant that the fix for WFPC would be simple enough in principle, and the HST's flaw had been quantified well enough that the project to implement the fix could go ahead. Likewise, plans for COSTAR developed by the Space Telescope Science Institute to compensate the aberration for the axial instruments could also be implemented with confidence.

The aberration of the HST also gave rise to the development of a variety of image restoration algorithms whose purpose is to recover as much as possible of the intended imaging performance of the telescope by removing the blurring effects of the aberration [Cf. ref 6].

# HST' PUI' 31, RE -1 MAGI NG AT WF/PC SECONDARY

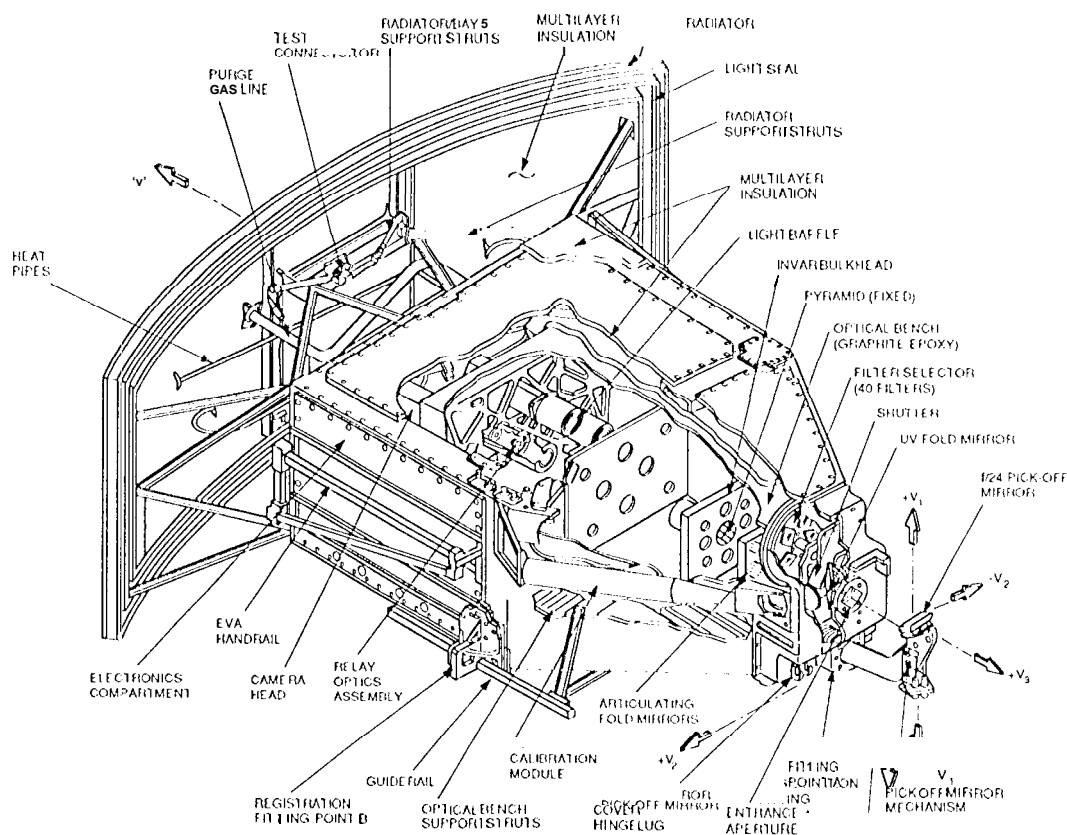
FIGURE 3.



## THE SECOND GENERATION WFPC

At the time HST was launched, and its optical flaw discovered, many parts of WFPC-2, including its optical components, had already been fabricated. However, the instrument was still about four years away from its planned date of completion. Under the pressure to recover from the defect of HST, the schedule to complete WFPC-2 was accelerated, and to its list of functional requirements was added the requirement that its optical system be modified to correct the spherical aberration of the telescope to the fullest possible extent. For the WFC the solution was to change the relay secondary shape to include an aberration equal and opposite to that in the HST. For the PC, a small previously flat "fold" mirror had to be made slightly convex so that HST primary mirror would be focused precisely on the relay secondary. The PC secondary could then be used in the same manner as that in the WFC. The specifications for the pre- and post-aberration optics are given in table 1.

## FIGURE 4.



in principle, these adjustments to the optical design of WFPC-2 are able to almost fully correct the flawed performance of HST over the full field of view of the instrument, provided the components are manufactured to tight (but realistic) tolerances, and provided the requisite alignment tolerances are also met. However, an entirely new constraint that did not exist for WFPC-1 is that the image of the HST primary formed on the corrective relay element must be precisely centered there, to within less than 1 percent, of its diameter. If this "pupil" contraction is not maintained, another aberration -- coma -- is introduced, quickly defeating the purpose of the corrective optical design and destroying the ability of HST to detect and resolve the faintest astronomical sources.

## Fixing the Aberration

To make the conceptual fix a reality, much work was needed. Some of the tasks to be undertaken were foreseeable at an early stage. The initial plan of attack included four key elements:

- to deduce accurately and with high confidence the actual error built into the HST optical system;
- to produce an appropriately revised optical prescription for WFPC-2 that will correct the HST aberration;
- to ensure by analysis that WFPC-2 will be properly located in relation to the HST focal plane;
- to accelerate the development of WFPC-2 by three years so as to meet a newly planned 1993 servicing mission launch date.

The first of these elements of the plan came to occupy the attention of many workers at JPL, the Space Telescope Institute, Goddard Space Flight Center, and in industry for a period of almost a year. Two main approaches were possible. The first involved a painstaking series of investigations of the tooling and test procedures used in manufacturing and testing the HST primary and secondary mirrors. The second approach involved diagnosis of the performance of the optical system using star images recorded by the observatory in orbit. It was clear that, high confidence in the conclusions of these diagnoses would be possible only if the two approaches led to essentially the same answers.

In fact, the "reverse engineering" of a severely flawed optical system from analysis of star images made with it is an ill-posed mathematical problem whose solution required the invention of new methods. In the course of it, a variety of technical approaches were proposed and investigated. From the proposed approaches ten were selected for detailed investigation by separate teams of experts; these are summarized in Table 1. An series of observations with the HST was undertaken to acquire a variety of stellar images for use in these analyses.



## TABLE 1

1. T. Banett and D. Sandler, *Recovery of Hubble Aberration Using an Artificial Neural Network*, Thermo Electron Technologies Corporation, T1 C-2179-R, May 17, 1992.
2. R. Lyon, P. Miller, and A. Gruszak, *Phase Retrieval Special Studies Task*, Hughes Danbury Optical Systems, Inc. PR 114-0313, June 4, 1991.
3. R. A. Gonsalves and S. M. Fstein, *Image Inversion Analysis of the Hubble Space Telescope Optical Telescope Assembly*, Electro-Optics Technology Center, Tufts University, May 15, 1991, revised November 1991.
4. J. R. Fienup, J. C. Marron, R. G. Paxman, T. J. Schulz, J. H. Seldin, and B. J. Thelen, *Image Inversion Analysis of the Hubble Space Telescope*, Environmental Research Institute of Michigan, 232 600-15-F, August 1991.
5. M. Shin, M. Colavita, R. Dekany, P. Dumont, B. Hines, M. Levine, D. Redding, S. Brewer, and A. Decou, *Image Inversion Analysis of Hubble Space Telescope Optics Using a Non-Linear Least Squares Algorithm*, Jet Propulsion Laboratory, October 18, 1991.
6. C. Roddier and F. Roddier, *Reconstruction of the Hubble Space Telescope Wavefront Distortion from Stellar Images taken at Various Focus Positions*, Institute for Astronomy, University of Hawaii, May 1991, revised October 1991.
7. M. Litvak, *Image Inversion Analysis of the HST OIA (Hubble Space Telescope Optical Telescope Assembly)*, TRW, 57661, March 15, 1991, revised July 18, 1991.

Measurements of the test tooling in 1990 showed that the apparatus used in making the HST optics contained one (and only one) significant error: a lens forming a part of the null corrector that was used in making the primary mirror was found to have been wrongly located by about 1.3 millimeters. As a result, the primary mirror of the HST would have been precisely polished to a hyperbolic shape but the hyperbolic shape would have had an incorrect eccentricity (or conic constant). Details of the analyses leading to this conclusion have been published elsewhere by ORA and Laurie Fury of HDOS.

The results of investigations of on-orbit images took longer to converge to a single answer. This was partly due to the need to gradually debug and perfect the computer algorithms that were newly being developed. When most of these investigations did converge, however, it was to a result that differed slightly, but significantly, from the answer provided by the test tooling - the so-called fossil evidence. The reason for the discrepancy was eventually discovered and understood: the optics in WFPC-1, while excellent enough to meet WFPC-1 specifications, were not perfect. When the contribution of the WFPC-1 optical imperfections (a small residual amount of spherical aberration) was determined from test records at JPL and taken into account, the difference between the manufacturing tooling and the analysis of on-orbit images was just what would be expected. The fossil evidence, therefore, could be trusted to represent to high precision the prescription of the optical system of the HST in orbit.

As a practical matter to meet an accelerated delivery schedule, it became necessary to commit to a corrective WFPC-2 optical prescription even before the final results of all of these

an early assessment of the conic constant (taken to be  $-1.0335$ ) for the HST primary, based primarily upon measurements of the test tooling. If subsequent investigation changed the estimate of the best value by a small amount (which in fact it did), an accommodation could be made: by an adjustment of the WFPC-2 focus. When this is done, the penalty in wavefront quality is insignificant, (less than  $2/1000$  waves rms) .

## MEETING NEW AND TIGHTER ALIGNMENT TOLERANCES

During the winter of 1990 and the Summer of 1991 great efforts were expended to determine the alignment stability of the camera using the available flight hardware anti the "on-orbit" results. The prime concern was the high sensitivity to pupil shear - a  $0.004$  inch ( $100$  micron) decenter of the secondary mirror, for example, would unacceptably degrade the performance of the system. Figure 5 shows the sensitivity to misalignment of the key optical and structural components.

## TOLERANCE TREE

FIGURE 5.

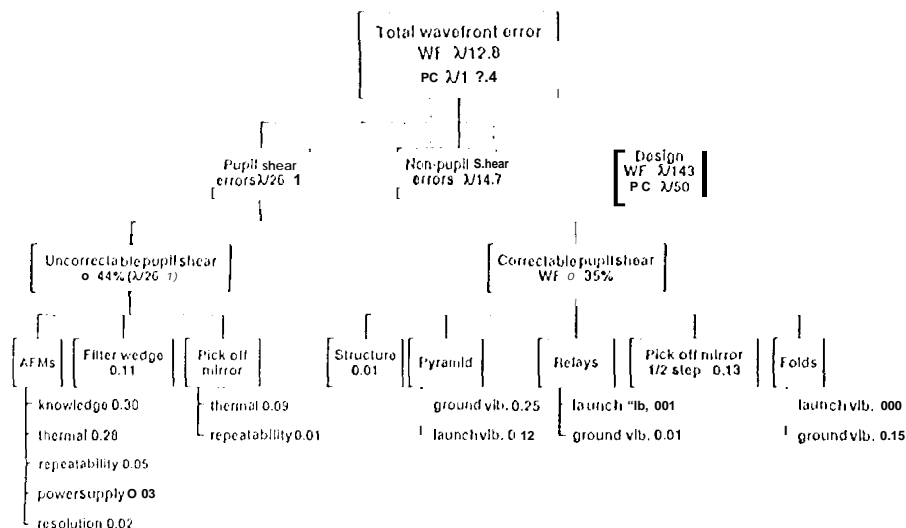


figure 3 Pupil shear error budget for fixed pyramid mirror

The ramifications of these concerns were extensive. It had been recognized that to avoid the introduction of coma, the proposed fix of the HST's spherical aberration would require that WFPC-2 be very accurately aimed relative to the telescope and that the required accuracy would likely exceed the capability of the three latches that anchor the instrument in place in the radial bay of HST. To allow for this fact, it was decided early in the program to provide an active tip-tilt mechanism to adjust the pickoff mirror; this would permit any anticipated latch error to be corrected by remote control from the ground.

However, concern also extended to the ability of WFPC-2 to maintain its alignment internally to the required level of accuracy, both during launch, and in flight. There was evidence that in WFPC-1, the internal alignment in orbit was slightly different from the alignment that had been documented just before launch. This would not have been a problem in WFPC-1 (had the HST been perfect), but might indicate the possibility of a problem in WFPC-2 because of its new sensitivity to pupil misalignment.

As a result of such considerations, JPL and the science team decided in September 1991 to recommend that a second level of active optics be implemented in WFPC-2, in the form of actively tip-tilt controlled fold mirrors in all but one of the relay optics channels of the instrument. To compensate for the added cost to develop and build the Active Fold Mirrors (AFMs), the decision was also made to eliminate four of the original eight channels of WFPC. In the resulting configuration, three of the channels would carry Wide Field Camera optics, while the fourth would carry Planetary Camera optics. In this arrangement, the active pickoff mirror would guarantee alignment of the channel having a fixed fold mirror. The three AFMs would guarantee alignment of the remaining channels. These recommendations were accepted and the task undertaken with utmost priority.

Even before the necessity of these measures had come under serious discussion JPL had undertaken a study in collaboration with Litton LITEK Optical Systems beginning in June 1991 to define a conceptual approach that would allow active control of the WF/PC-2 pupil alignment on-orbit. The approach was to capitalize on LITEK's proven electrostrictive actuator technology and optical capabilities. The result of this study, which is discussed at length in other papers in this session, demonstrated that active pupil control was technically feasible. To make it a reality required, however, that LITEK and JPL work closely together to develop, flight qualify and deliver a set of flight articulated light mirrors in nine months. This required a significant resource commitment and a radically different approach to implementation. The development of the articulating fold mirrors

was successful both technically and programmatically: the mirrors were available when needed to support the camera build up, they were completed within cost, and they performed as advertised.

It remains to mention a final modification that also stemmed from the very tight, alignment tolerances in WFPC-2. Among possible causes of the on-orbit alignment variations suspected in WFPC-1, the highly complex pyramid mirror mechanism became a leading suspect. In WFPC-1, this mechanism provided two capabilities: by moving the pyramid mirror axially it could be used to adjust the focus of the instrument relative to the telescope, and by rotating the pyramid mirror  $\pm 45$  degrees around its axis it served as an optical "switch" between the WFC and PC channels. The latter capability was no longer needed in the clc-scoped 4-channel WFPC-2 configuration. Moreover, the focus capability could no longer be used in WFPC-2, because if the pyramid were to be moved axially, pupil misalignments would be created that would give rise to coma in all four channels. On the other hand, if small adjustments in the focus of WFPC-2 relative to the other instruments proved to be necessary in orbit, the necessary capability exists in the HST and in COSTAR to adjust the focus. For these reasons, the decision was ultimately reached to replace the original pyramid mechanism by a fixed mounting so as to eliminate, insofar as possible, all risk of optical misalignment in the instrument.

At the present time the camera has all optical elements integrated and successfully tested. The optical performance, is significantly better than originally anticipated. The camera is now in the final stages of integration. Flight acceptance testing including a lengthy Science Calibration in thermal vacuum is planned to be complete in early June. Following this, the instrument will be shipped to the GSFC for testing with the HST simulation equipment to ensure compatibility in orbit. The Servicing Mission is currently scheduled for launch in late November/early December 1993. With luck we will have images by Christmas that demonstrate the full capability of the 2.3 meter mirror.

#### REFERENCES

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[3] Lew Allen, Roger Angel, John D. Mangus, George A. Rodney, Robert R. Shannon, and Charles P. Spaelhof, The Hubble Space Telescope Optical Systems Failure Report, NASA TM-103443m November 1990.

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